

The Mars Thermal Environment and Radiator Characterization (MTERC) Experiment

Kenneth R. Johnson and David E. Brinza

Jet Propulsion Laboratory, California Institute of Technology

Copyright © 2000 Society of Automotive Engineers, Inc.

ABSTRACT

Radiators will be used on Mars to reject excess heat from various processes and surfaces and will help temper the climate of any future manned habitats. Radiator performance is a function of the radiator size (area), the emissivity, ϵ , of the radiator surface, the radiator temperature, local environmental conditions, and the effective sky temperature to which it radiates. The effective sky temperature of Mars is not known. Previous estimates have ranged between 80 K to 170 K. Also, it is not known how dust accumulation and other environmental effects act to change the performance of a radiator as a function of time. The MTERC Experiment is designed to gather data to address these unknowns. This paper will describe the operational theory and the configuration of the MTERC experiment hardware and will discuss results of MTERC performance testing.

INTRODUCTION

In-situ resource utilization (ISRU) is a fundamental, key technology for human exploration of the solar system. In-situ propellant production (ISPP) is the nearest term aspect of ISRU and represents the bridge between robotic exploration and human exploration of Mars. ISPP involves producing propellants at the site of exploration using indigenous planetary resources and, if necessary, Earth-supplied consumables. ISPP concepts for Mars primarily consider atmospheric carbon dioxide (CO_2) as the most readily available in-situ resource for the production of oxygen (O_2) and possibly a hydrocarbon fuel. In general, any conceivable robotic or human exploration mission on Mars that utilizes an ISPP process will have to reject heat to the Mars environment with radiators. Currently, because there is a lack of knowledge regarding the rate of heat loss from a radiator to the Mars environment, significant uncertainty exists in sizing radiators optimally, and in determining the possible need for periodic radiator cleaning. Although the MTERC experiment development was primarily aimed at providing data for design of ISPP systems, the need for general heat rejection (not necessarily related to ISPP) from other Mars Lander systems would make MTERC data beneficial for design of future Landers. Finally, Mars climatologists and instrument designers would benefit from an independent measurement of the effective sky brightness temperature. MTERC is one of five

experiments to be included on the Mars In-Situ Propellant Production (ISPP) Precursor (MIP) experiment package which was intended to be mounted on the deck of the Mars 2001 Surveyor Lander. The purpose of MIP is to demonstrate the performance of various ISPP processes in-situ on Mars. The demonstrated ability to produce propellant in-situ using Mars resources is considered to be a necessary precursor to any future manned mission to Mars.

Radiators operating on the Mars surface will receive heat by conduction from the various heat loads and will reject heat by conduction and convection to the local "air", and by radiation to the sky. Conductive and convective heat transfer to the local "air" is characterized by a convective heat transfer coefficient, h_c . In recent testing of the Mars Pathfinder spacecraft and the Mars rover Sojourner at JPL, measurements of h_c in simulated Mars surface environment conditions (at windspeeds from 0 m/sec to about 5 m/sec) yielded h_c values of between 1 and 2 $\text{W/m}^2\text{-K}$. The expected operating range of an ISPP sorbent pump radiator will be from a high of about 330-350 K to a low of about 160-200 K. As the radiator temperature decreases, it may fall below the local air temperature, at which point heat transfer by convection will add to rather than remove heat from the radiator. Each night the radiator will eventually come to a quasi-steady state temperature when all heat loads are balanced; likely at a temperature below the local air temperature.

At this point it is prudent to ask the question, "Which is the more dominant heat rejection mechanism during cooldown, conduction/convection to the local air or radiation to the night sky?" Using a range of values for h_c (0.5 to 2.5 $\text{W/m}^2\text{-K}$), and a range of values for radiator ϵ (0.02 to 0.92), and assuming an air temperature of 200 K, the ratio of radiative/convective heat rejection was calculated. These calculations show that, at an air temperature of 200 K, as long as the radiator ϵ remains greater than ~0.6, radiation will be the dominant heat rejection mode (with few exceptions) for radiator temperatures throughout the expected 200 to 350 K operating range of the MAAC hardware for any night sky temperature below 180 K. Since Mars surface atmospheric temperatures during night time have been estimated to be typically around 200 K (or lower) at moderate latitudes, it can be seen from these calculational results that for this condition, radiators would be sized primarily by the rate of

radiative heat loss to the sky and secondarily by the convection heat loss to the local air. The degree to which the radiative heat loss mechanism remains dominant over the convective heat loss will be a function of how cold, dusty and windy the local Mars surface atmosphere is, and how clean the high- ϵ radiator surface remains in this atmosphere.

The MTERC experiment was designed to determine accurate values for the effective sky brightness temperature on Mars. An accurate measurement of the effective sky brightness temperature on Mars will provide critical knowledge needed to optimally size the various radiators required for ISPP. Because radiative heat transfer is a function of the difference between the fourth powers of the temperatures of the radiating sources, if the actual effective sky brightness temperature is sufficiently low (e.g. less than ~ 130 K), it will not be necessary to know the exact value of the night sky temperature in order to size radiators properly. It would be enough to know only that the temperature is less than say, 130 K. At this low temperature, the downward IR flux from the sky impinging on a radiator will be very small compared to the upward IR flux from the radiator to the night sky.

The rate of heat transfer by radiation is dependent upon the emittance of the radiating surface and the radiator view-factor to the sky. The Mars atmosphere is laden with dust which can deposit on radiator surfaces, and possibly erode them, either by impact from windblown dust or by any reactive oxidants that might be adsorbed on the dust. A high- ϵ , horizontal radiator surface may, over time, degrade to a lower- ϵ radiator surface if it has been coated by enough settling dust. Therefore, it is very important to measure the rate of radiator ϵ degradation (and whether or not this degradation reaches some steady state value after which further dust cover or coating erosion has no further negative effect on radiator performance) in order to effectively design full-scale radiators for subsequent ISPP systems. Measurements of the surface ϵ degradation as a function of time will provide important data to designers of subsequent ISPP radiators to allow them to account for these degradation effects or to determine how to counteract these effects by means of a mechanism to periodically clean the radiator. Therefore, the MTERC experiment was designed to provide measured values of the equally important long term effects of radiator surface degradation on radiator performance.

MTERC CONCEPTUAL DESIGN STUDIES

The initial concept for the MTERC experiment included a radiator encased inside a small evacuated vessel fitted with a cesium iodide window. The theory was that the radiator would be mounted in such a way that it was highly insulated conductively from the vessel so that the rate of conductive heat transfer from the radiator would be very low, and would be considered negligible as compared to heat transfer by radiation. Furthermore, since the radiator was to be mounted inside an evacuated volume, the convective heat transfer could be assumed to be negligible as well. Therefore, by far, the dominating mode of heat transfer would be radiative. By allowing the radiator to reach a steady state temperature during the night, a direct calculation of the sky

temperature could be made as long as the temperature of the radiator could be measured accurately. The radiator surface would always remain clean since it would be encased inside the vessel.

Early in the investigation of this design, in April/May 1997, several critical flaws with this design were found. First, the cesium iodide IR transmitting window would need to be a massive 1/2" thick in order to withstand the launch loads (if a flat window was to be used) or even more massive if a domed hemispherical window was to be used. The domed concept was studied because it was thought that dust would not accumulate on a domed glassy surface. A flat window would require a cover (to maintain cleanliness and to minimize daytime heat load inside the vessel) which implied motor driver electronics to operate the cover. Either a domed or a flat window would have very considerable thermal mass and would take a long time to reach steady state temperature itself during the night. Further, unless the temperature of the window could be known accurately, there would be no way of calculating the thermal effect that the window would have on the overall determination of the night sky temperature. There was no good way for mounting a thermocouple on the window without it being in the field of view of the radiator and thereby affecting the outcome of the radiator temperature measurements. All these problems would pale in significance if the vacuum inside the vessel was lost due to a seal failure. Loss of vacuum inside the vessel would negate the assumption of negligible convective and conductive heat transfer. This last factor killed the concept because there was a low likelihood that a completely leak tight seal could be implemented which would seal the vessel well enough to be able to maintain a high vacuum environment throughout the life of the mission. No conceptual drawings are presented here since only sketches of this design concept exist.

Subsequent MTERC design investigation led to the consideration of six different conceptual design options. Following a detailed analysis of these options the MTERC design presented below was selected for development unit fabrication.

MTERC CONCEPTUAL DESIGN

The basic design approach for the MTERC development unit involves the use four radiators, one pair normally covered to keep their surfaces pristine and a second pair always exposed to allow environmental effects to alter their surface properties as a function of time, erosion, settling dust, UV degradation, etc. Each radiator pair consists of one radiator that has a high- ϵ surface and one that has a low- ϵ surface. All four radiators are mounted identically on individual thermal shielding (insulating) structures that minimize thermal conduction to a negligible value. Identical heaters are installed on the bottom side of all four radiators, one for calibration and one for active heating. During operation, only one radiator pair is studied at any given time. By heating the radiator with the higher- ϵ surface to match the temperature of the radiator with the lower- ϵ surface, the convective and conductive heat loads from the two radiators in this condition can reasonably be assumed to be identical. Figure 1 illustrates this MTERC design concept.

The heat balance equations on both plates are:

for low- ϵ radiator:

$$Q_{\text{conv}} + Q_{\text{parasitics}} = Q_{\text{rad (ref)}} = \epsilon_L A \sigma (T_{\text{rad}}^4 - T_{\text{sky}}^4) \quad (1)$$

for high- ϵ radiator:

$$Q_{\text{conv}} + Q_{\text{parasitics}} + Q_{\text{heater}} = Q_{\text{rad (act)}} = \epsilon_H A \sigma (T_{\text{rad}}^4 - T_{\text{sky}}^4) \quad (2)$$

Since the radiator temperatures are exactly the same and are configured with heaters and temperature sensors mounted in identical locations, Q_{conv} and $Q_{\text{parasitics}}$ will also be the same for both radiators, and subtraction of (1) from (2) along with subsequent manipulation yields:

$$T_{\text{sky}} = \left[T_{\text{rad}}^4 - \frac{\Delta Q_{\text{htr}}}{(\epsilon_H - \epsilon_L) A \sigma} \right]^{\frac{1}{4}} \quad (3)$$

This result implies that it is not necessary to have knowledge of either convection or conduction parasitics in order to determine the sky temperature. This method allows for canceling out parasitic effects such as PRT self-heating as long as the two radiators being compared are mounted, instrumented and configured identically, and are at the same temperature. Even so, the radiators must still be kept clean (to preserve knowledge of the true values for emissivities) and the heater must be capable of producing accurately measured and controllable low-level power outputs.

Using this same temperature-equalization methodology, the long-term effects of the Mars environment on radiator performance (the change in ϵ) can be determined. Consider that two pairs of radiators are initially configured exactly as described in the previous paragraph. On Mars, one pair of radiators is left exposed and becomes "dirty" while the other pair is covered most of the time and for all intents and purposes is considered "clean." By measuring the ΔQ_{htr} power needed to bring a "clean" radiator to the temperature of an identical "dirty" radiator, and by assuming that T_{sky} is known (having just been determined previously by application of Eqn (3) to the covered radiator pair), the emissivity difference between the clean and dirty radiators, $\Delta\epsilon$, can be determined.

The heat-balance equations for the two radiators having the same initial emissivity, but with one "clean" and one "dirty", are as follows:

for "clean" plate:

$$Q_{\text{conv}} + Q_{\text{parasitics}} + Q_{\text{heater}} = \epsilon_c A \sigma (T_{\text{rad}}^4 - T_{\text{sky}}^4) \quad (4)$$

for "dirty" plate:

$$Q_{\text{conv}} + Q_{\text{parasitics}} = \epsilon_d A \sigma (T_{\text{rad}}^4 - T_{\text{sky}}^4) \quad (5)$$

Again, if radiator temperatures are the same, then Q_{conv} and $Q_{\text{parasitics}}$ are equal for both radiators.

Subtraction of (5) from (4) eliminates these terms and subsequent manipulation yields:

$$\epsilon_d = \epsilon_c - \frac{\Delta Q_{\text{htr}}}{A \sigma (T_{\text{rad}}^4 - T_{\text{sky}}^4)} \quad (6)$$

where the value of T_{sky} was calculated from a previous run and ϵ_c is assumed to be known and constant. An emissivity degradation factor ϵ_d/ϵ_c can be calculated and tabulated or plotted as a function of time.

One primary concern arises regarding the use of this method for determining ϵ_d . If ΔQ_{htr} is too small when comparing the two high- ϵ radiators then the certainty of the determined value for ϵ_d may be suspect. However, once the effective T_{sky} temperature has been determined by Eqn (3), ϵ_d can be calculated by using the ΔQ_{htr} value measured between the clean low- ϵ radiator and the exposed high- ϵ radiator. The determined value for ϵ_d will be just as valid and may be more accurate than that calculated from ΔQ_{htr} data obtained by comparing both high- ϵ radiators.

Implementation of this design required development of a differential temperature control circuit (DTCC) which can control the amount of heat added to the colder high- ϵ radiator in order to raise its temperature to match that of the warmer low- ϵ radiator. Such a DTCC had been previously built at JPL (for the Active Cone Radiometer flight experiment) that had the characteristics necessary to provide the accurate heater power control required by MTERC. Figure 2 presents a functional block diagram of the DTCC. By matching radiator temperatures, both radiators experience the same thermal environment, allowing accurate ΔQ_{htr} comparisons to be made without the need to consider changes in the Mars ambient thermal environment over time.

Figure 3 shows the ΔQ_{htr} values required for raising the temperature of a 16 cm² radiator with an emissivity of 0.9 to match the temperature of another 16 cm² radiator with an emissivity of 0.1; determined for five different sky temperatures (100 K, 120 K, 140 K, 160 K, and 180 K).

It is important to note from this figure that for a particular radiator temperature, the sensitivity of the method diminishes as the absolute sky temperature decreases, because the differences between values of ΔQ_{htr} corresponding to different sky temperatures diminishes, making it more difficult to resolve differences in sky temperature from differences in heater power. For example, for a radiator temperature of 200 K, the difference between required values of ΔQ_{htr} for sky temperatures of 180 K and 160 K is 28 mW, whereas the difference between required values of ΔQ_{htr} for sky temperatures of 140 K and 120 K is 12.8 mW. Thus, the measurements innately become less accurate at the lowest sky temperatures. Therefore, using this approach, the minimum radiator size to be used for the MTERC experiment is governed by the resolution of the DTCC ΔQ_{htr} measurement. From this example, using 16 cm² radiators, it can be surmised that the DTCC must be able to resolve ΔQ_{htr} to $< +10$ mW in order to be able to determine T_{sky} within roughly $< \pm 10$ K. If the sky temperature is 130K or lower, it may be difficult to

estimate T_{sky} accurately but it will be possible to assert that T_{sky} is 130K or lower. Since $< \pm 10$ mW is about the lower limit of resolution of the DTCC, the minimum size for the breadboard MTERC radiators was set at 16 cm^2 . The actual radiator size that was used in the MTERC experiment is 34.2 cm^2 . Also apparent in this result is that the two radiators being compared should have as widely disparate emissivity values as possible in order to yield a ΔQ_{hr} high enough to be able to be measured accurately with the DTCC.

To start a typical measurement session at night, both the high- ϵ radiator and its companion paired low- ϵ radiator are allowed to reach a nominal steady state condition in the unheated mode after opening the cover. The "unheated" steady state temperatures is recorded and then the colder radiator is heated to match the temperature of the warmer radiator. The matched temperatures of the two radiators are allowed to stabilize to a steady state condition for two hours, and then the heater power needed to sustain this steady state condition is recorded. Then, by applying Eqn (3), a value for T_{sky} can be determined.

By a similar technique, long-term environmental effects can also be quantified. At the beginning of a test run, the "clean" radiators are uncovered and a run is initiated to compare the "clean" low- ϵ radiator with the uncovered "dirty" high- ϵ radiator. This first comparison is done over a two hour time period. Next, after this first run is complete, the two "clean" radiators are compared to determine a value for T_{sky} . This data set is also collected over a two hour time period. Finally, a run is initiated to compare the "dirty" low- ϵ radiator with the uncovered "clean" high- ϵ radiator. Again, a two hour time allotment is provided to allow the system to reach steady state. To finish the run the cover is re-closed. The determined T_{sky} value is used in the Eqn (6) calculation for ϵ_d for each of the two exposed "dirty" radiators. Then the newly calculated values of ϵ_d can be compared against the initial values of ϵ_d to determine a degradation ratio against the initial state. Plots of ϵ_d with time will indicate the rate at which any measured degradation is occurring.

MTERC DEVELOPMENT UNIT DESIGN

Once the radiators had been sized, the rest of the design could proceed. The radiator thermal shields on which the radiators are mounted are configured in an inverted pyramid shape so that their footprints are minimized to limit conductive heat transfer to the thermal equalizer plate below. The thermal shields were fabricated from $0.015''$ ($\sim 0.4 \text{ mm}$) thick e-glass composite material to provide lightweight strength and low thermal conductivity. A thermal equalizer plate (also constructed of e-glass) serves as the mounting base for the thermal shields and its elevated mesa-like surface is thermally well isolated from its lower flange where it interfaces with the MTERC/MIP interface plate (which in turn mounts to the MIP structure). The top surface of the thermal equalizer plate mesa contains an embedded layer of heat-conducting carbon-carbon fiber to promote isothermality. A dust shield is provided to surround the normally covered radiator structures to prevent dust from settling onto the normally covered radiators or their substructure. The dust shield is designed with its top edges at about 1 mm above the top of the

covered radiator surfaces so that when the cover is closed, the covered radiators are "sealed in". A wind shield is designed to similarly protect the normally exposed radiator structures so that the convective heat transfer for both sets of radiator substructures (normally covered pair and the exposed pair) can be assumed to be equal. Also, the wind shield is designed so that its top edges lay just below the bottom surface of the exposed radiator mounting flanges on the thermal shields with a small gap between the top edge and the flange bottom side to ensure that there is no thermal contact between the wind shield and the radiators. The top surface of the wind shield is rounded inboard so that any dust that might collect in the gap would have a tendency to fall to the base of the thermal equalizer plate mesa and thus have no thermal effect on the MTERC experiment.

Aluminized mylar is applied to the external surface of the thermal shields to minimize any radiative heat transfer effects from the dust and wind shield surfaces. Aluminized mylar also is applied to the internal surface of the thermal shields to minimize heat gain from the radiator heaters so that it can be assumed that all thermal energy (power) applied to the radiator heaters is transferred conductively to the radiators and a negligible amount is lost radiatively to the thermal shields.

Mounted on the bottom side of the each radiator are: 1) five 1250 ohm resistors, having stable resistance values independent of temperature, wired in parallel to provide an effective resistance of 250 ohms, to serve as the "active heaters", 2) one 2000 ohm resistor, also having a stable resistance value independent of temperature, to serve as the "calibration heater", and 3) a 4-wire platinum resistance thermometer (PRT) to accurately monitor the radiator temperature to within 0.1°C . The resistors and the PRT are wired using low-conductivity manganin wire to limit parasitic heat loss from the radiators. The 9-wire bundle from each radiator (two for each heater circuit, four for the PRT and one ground) is fed down through a hole at the base of the thermal shield and is staked to the bottom surface of the thermal equalizer plate. Each manganin wire is spliced to a teflon-insulated copper wire and the four 9-wire bundles are fed through individual holes in the MTERC/MIP interface plate where they are bundled into a 36-wire harness. This wiring harness is then further bundled with the 11-wire harness from the motor/cover assembly and the wiring is routed to the MTERC electronics printed wiring boards.

The motor/cover assembly design was equally challenging. The motor chosen is the same type as that used to drive the Mars Pathfinder Sojourner rover wheels. This motor not only is already flight-rated but it also has flight heritage. A motor mounting structure houses the motor inside an insulator tube to both isolate the motor from the raw Mars environment and protect the delicate motor and gearbox works from Martian dust. An aluminum bracket is provided to hold the insulator tube (motor housing) in place and to keep it and the motor body from rotating as the motor shaft turns. Cutouts are removed from the aluminum bracket to reduce mass. The cover is made from a carbon-carbon composite material to be light weight and have high stiffness. The motor shaft serves as an axle to the cover hub on one side

while the potentiometer shaft serves as the cover's other hub axle. With this design, the potentiometer provides data feedback to indicate the cover position as the motor turns. The potentiometer is mounted in a specially designed spool that fits snugly inside the ID of the insulator tube. Since the motor should not be run unless its temperature is $> -70^{\circ}\text{C}$, film heaters are mounted on the motor to preheat it if necessary before operation. A 4-wire PRT is mounted on the motor body to provide motor temperature data. Electrical wiring (11 wires: 4 PRT, 2 motor drive, 2 motor heater, 3 potentiometer) is routed out through a hole on the side of the insulator tube. Figure 4 presents a functional block diagram of the motor and position sensing controls.

The electronics circuitry required two printed wiring boards (PWBs) sized 4" x 6" (101.6 mm x 152.4 mm) each. One PWB was used to mount the DTCC circuitry, the motor control circuitry and the digital to analog converter. The other PWB was used to mount the command and data handling (CDH) circuitry. Circuit layout of the PWBs was a big challenge because of the MIP-imposed dimension constraint. A field programmable gate array (FPGA) was used for the CDH PWB to minimize the number of packaged chips needed for the CDH board. The circuitry designs were completed by mid-July 1998 allowing board layouts to begin. The CDH PWB was delivered in mid-October and the DTCC PWB arrived in mid-November. Parts installation was completed in late-December. Concurrent to parts installation, the control software was developed. Electronics troubleshooting started on 12/23/98, just in time for Christmas! The software loaded the first try, but unfortunately, most MTERC functions didn't work right that first day.

The software was written in assembly language using the MCS-51 instruction set. The CDH system provides a real time clock for time stamping the data, session operations sequencing, 16 channel data transmission at one second and one minute intervals, mux controls for selecting the radiator pair to be compared, setpoints for the calibration heater controls, setpoints for the motor drive controls, and MIP μP communications. MUX selects are handled through the FPGA. The CDH performance and memory margins are large relative to the required performance. Sequence ("Session") modifications are simple to implement. Figure 5 illustrates the functional block diagram of the CDH circuitry. The basic MTERC/MIP communications scheme is illustrated in Figure 6.

Electronics troubleshooting continued through January and February of 1999. Finally, at the end of February 1999, all MTERC functions and sessions were operative and the development unit was ready for delivery to JSC. At that time, JSC was hurriedly preparing for the integrated MIP development unit test and so there was no time left for the MTERC team to conduct MTERC testing in a simulated Mars environment at JPL before delivering the development unit hardware to JSC. Only room temperature bench top tests were conducted. Unfortunately, an MTERC software problem in a health check routine prevented the acquisition of any useful MTERC session data throughout the MIP development unit test at JSC.

MTERC DEVELOPMENT UNIT TESTING

In late August 1999, just prior to the MTERC critical design review (CDR), the MTERC hardware was tested in a simulated Mars environment at JPL. Figure 7 illustrates the test setup. Tests were conducted with simulated Mars sky temperatures at 170 K, 150 K, 130 K and 110 K. A cryocooler was used to cool a skyplate fixture that surrounded the MTERC radiator assembly to simulate the sky temperature. A multi-layer insulation (MLI) blanket was wrapped around the top of the fixture to totally enclose the MTERC hardware.

Tests were conducted both at vacuum and at simulated Mars environmental conditions. Figure 8 shows the calculated sky temperature as a function of radiator temperature for a test conducted in vacuum. In this test, one can see that the calculated sky temperature is quite insensitive to changes in radiator temperature. Even though the radiator temperature changed from 155 to 185 K the calculated sky temperature does not change more than a few degrees. Figure 9 shows how well the DTCC functions to track changes in the reference radiator temperature. As the input power from the reference radiator calibration heater is changed, the DTCC active heater circuit responds immediately to equalize the temperature of the active radiator with that of the reference radiator. Figure 10 plots the calculated sky temperature as a function of time using the same test run data as that used for Figure 9. Figure 10 again illustrates that the sky temperature determination is insensitive to changes in the radiator temperature.

From these test results, it can be concluded that the MTERC DTCC equalizes the temperatures of the two radiators typically within 45 minutes after start-up. Transients caused by changes to the calibration heater settle within 30 minutes. The calculated sky temperature varies less than 5 K with a corresponding 25 K change in radiator temperature (in vacuum). Also, calculated sky temperatures are within 3 K to 12 K (always higher) from the actual skyplate temperature over the range of 160 K to 120 K. The probable cause of the over-estimation of the calculated sky temperature is attributable to the radiative parasitic heat load from the higher temperature MLI surface. To correct this source of error, the JPL test setup will be modified to ensure that this radiative heat load is eliminated. An additional aluminum plate, coated with a black high emissivity paint, will be added to the top of the skyplate fixture to totally enclose the MTERC radiators within a temperature controlled volume. The MTERC team plans to conduct a set of tests on the Flight hardware using this modified test setup to calibrate the MTERC experiment.

MTERC QUALIFICATION UNIT DESIGN AND FABRICATION

The MTERC qualification unit is designed essentially the same as the development unit except that the motor/cover assembly is mounted 90 degrees counterclockwise from its location on the development unit. This change was requested by the Mars 2001 Surveyor Lander design engineers to

accommodate interface requirements for other Lander payloads. Since the MTERC radiator assembly was not square, considerable re-dimensioning (and also considerable redesign) of the MTERC wind shield, dust shield, cover and motor/cover linkages needed to be done before qualification hardware could be built. Nonetheless, by early December 1999, the new hardware had been re-designed and built, electronics and software problems had been found and fixed and the MTERC qualification hardware was delivered to JSC on 12/7/99. Figure 11 is a photo of the MTERC Qualification Hardware taken just prior to delivery to JSC.

MTERC QUALIFICATION UNIT TESTING

On 12/7/99, the MTERC qualification hardware was mounted onto the MIP structure and, subsequently, the functionality of the data and command communications with the MIP control microprocessor was tested and shown to be working properly. The cover open/close tests were done to demonstrate that MIP communication had been positively established. Since the MIP team was busy integrating other experiments onto the MIP structure, the motor/cover test was the only test conducted at JSC prior to the pre-qualification thermal test conducted in late-January, 2000.

Two major anomalies of the MTERC hardware were identified during the pre-qualification thermal-vacuum test at JSC. First, the radiator temperature values for all radiators were inaccurate when the MTERC hardware was at a temperature below -20°C . The failure symptoms seemed to indicate that an open circuit occurred when the temperature got cold. Second, the MTERC radiator cover did not fully close at temperatures around -30°C and below because of a mechanical interference problem with the dust shield.

In February 2000, the MTERC circuitry was tested at ambient temperature and pressure and found to have no open circuits. Subsequently, the MTERC experiment was operated at room temperature and no anomalous functionality was observed. Everything worked as it should! It was hypothesized that there was likely a bad solder joint on the exposed high- ϵ radiator PRT circuit that may be causing the problem. MTERC was reinstalled onto the MIP structure and subjected to the qualification vibration testing and the thermal testing (worst case hot and cold). Following vibration testing, MTERC was bench checked at room temperature and no MTERC failures were detected. However, during the subsequent Qualification Unit thermal testing, the bad radiator temperature reading problem recurred. Further, the cover interference with the dust shield also recurred. As a result of these two problems, no further useful data was obtained during the MIP qualification unit testing. Both problems need to be resolved before MTERC Flight hardware delivery.

MTERC FLIGHT UNIT DESIGN

In mid-April 2000, the MTERC flight unit hardware design was reviewed by a select review board at JPL and design modifications are now underway at the time of this writing. Proposed design changes

include: 1) changing the type and insulation-rating of the manganin wire that attaches the radiator heaters to the connector cabling in order to ensure that the proper cryogenic-rated wiring is used; 2) have a cryocooler technician familiar with the special handling requirements for manganin wire perform the soldering of the manganin wire connections; 3) mount the manganin wire to the bottom side of the thermal equalizer plate instead of the bottom of the MIP interface plate to ensure that the manganin wire never comes in contact with any metallic surface (the MIP Faraday EMI shield for example) so any potential for shorting to the chassis is drastically reduced by design; 4) trim the flaps from the edges of the cover to ensure that any mechanical interference between the cover flaps and the dust shield will be eliminated by design; and 5) make the necessary software corrections to the date stamp on the data file as well as any other outstanding software issues that may still exist.

For the MTERC Flight Unit, both normally covered and exposed high-emissivity radiators will be coated with S13GP/LO-1 white paint and both low-emissivity radiators will be coated with Parylene Type C. Coatings will be applied to identically sized aluminum substrates. The rationale for this design decision is presented below.

The original radiator coating selection for the MTERC development unit consisted of two gold (exposed, covered), one white (exposed) and one black (covered) elements. Thermal analysis has shown that the gold radiator, when exposed to maximum solar irradiance on Mars, could exceed 175°C . Temperatures this high could permanently damage the MTERC hardware. In order to avoid catastrophic overheating, the low- ϵ radiator requires an α/ϵ of no greater than 2. The measurement resolution of sky temperature or emissivity changes is improved by having a significant emissivity difference between the low- ϵ reference and high- ϵ active radiators to increase the differential power dissipated in the active radiator. A thin coating of parylene on polished aluminum can serve as a stable, low- ϵ surface for the reference radiators and will have a pristine low ϵ value of about 0.2.

In order to measure changes in solar absorptance, it is desirable to operate MTERC with the two high- ϵ radiators as the active/reference pair. This requires daytime MTERC operation with the deployable cover open. The case with Cat-a-lac black on the (generally) covered high- ϵ radiator was examined. The maximum (worst-case) differential solar power absorbed at beginning of life for the Cat-a-lac/S13GP/LO-1 radiator pair is over 1.6W. The MTERC active heater can deliver a maximum of 1.5W. The maximum temperature reached by the black coating (near local noon) is about $+50^{\circ}\text{C}$. At this relatively high value, a large temperature differential develops between the radiator and the MTERC radiator assembly base. Differences in thermal conduction between the radiator and the base of radiator pairs is a source for error in the MTERC data analysis. A condition where radiators are hot and the base is cool increases the contribution to this error term. The case with both high- ϵ radiators coated with the S13GP/LO-1 white paint was also examined. The beginning-of-life radiators reach a maximum temperature of -35°C . If

the value of solar absorptance increases by only 0.01 as a result of radiator degradation, the amount of increased solar radiation absorbed is approximately 20 mW, a value which can be measured by MTERC with an accuracy of about 30%. This indicates that in the dual S13GP/LO-1 white paint configuration, MTERC should easily detect changes in solar absorptance of 0.05. Therefore, S13GP/LO-1 white paint was selected for the surface coating for both the high- ϵ radiators.

To characterize the MTERC radiator coatings, measurements of solar absorptance will be made at room temperature. Emissivity measurements will be made as a function of temperature down to -110°C . The initial measurements on Mars will serve as the baseline for subsequent degradation due to environmental exposure.

CONCLUSIONS

Testing of the MTERC Flight hardware will take place soon. It is expected that test results will show that the MTERC experiment will be able to determine the effective sky temperature to within $\pm 5\text{K}$ throughout the 120 to 180 K range.

The following success criteria is proposed for the MTERC experiment. If MTERC, comparing the exposed radiators, can determine the Mars sky temperature with uncertainty better than $\pm 10\text{K}$ then MTERC will be deemed a Minimum Success (50%). If MTERC, comparing the normally covered radiators, can determine the Mars sky temperature with uncertainty better than $\pm 5\text{K}$ then MTERC will be deemed a Partial Success (75%): A Partial Success rating would also be given if MTERC meets the minimum success criteria and provides data to characterize exposed radiator degradation due to environmental effects (solar absorptance or emittance change of 0.05) over 60 sols. MTERC will be deemed a Complete Success (100%) if it validates sky temperature measurement using covered radiators with computed accuracy better than $\pm 5\text{K}$ and MTERC characterizes exposed radiator degradation due to environmental effects (solar absorptance or emittance change of 0.05) over 90 sols. If MTERC provides Mars wind and dust assessment data on hourly time-scales then it should receive a Above and Beyond Expectations (150%) rating.

The MTERC experiment offers the first opportunity to accurately determine the effective sky temperature of Mars. Further, MTERC is designed to characterize performance degradation of radiators on Mars as a function of time. If successful, MTERC will provide very valuable data for thermal designers of future Mars craft and habitats. The MTERC team has worked hard to ensure this success.

ACKNOWLEDGMENTS

The research and development work described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

The authors wish to thank NASA for supporting this research and development work. We especially thank the MIP Principal Investigator, David Kaplan, for his efforts in providing the opportunity for JPL to perform this interesting work. Thanks goes to Don Rapp at JPL for initially proposing the MTERC experiment and for providing guidance during the early stages of the conceptual design and development. We would like to recognize Ted Ozawa at JPL for developing the DTCC circuitry, and Jim Tomey for helping to breadboard this circuitry and to debug the PWB electronics. Further, we wish to recognize Dale Winther at JPL for developing the CDH circuitry design as well as the MTERC control software. Special thanks to Gina Alleruzzo and Carolina Flores-Helizon for installing the electronics parts on the PWBs and assisting with the troubleshooting of problems on these boards. Also special thanks to David Fletcher at JSC for his contributions in leading the MTERC development unit and qualification unit testing at JSC and to Katy Hurlbert at JSC for providing technical insight into MTERC radiator coating selections. Finally, the authors wish to recognize the contributions of Ken Juanero, an ex-JPL employee who helped formulate the conceptual design of the MTERC experiment and who led the MTERC development unit fabrication effort.

CONTACT

Kenneth R. Johnson, California Institute of Technology, Jet Propulsion Laboratory 4800 Oak Grove Drive, MS 125-177, Pasadena, CA 91109, USA. Phone: 818/354-2040, Fax: 818/354-8153, kenneth.r.johnson@jpl.nasa.gov

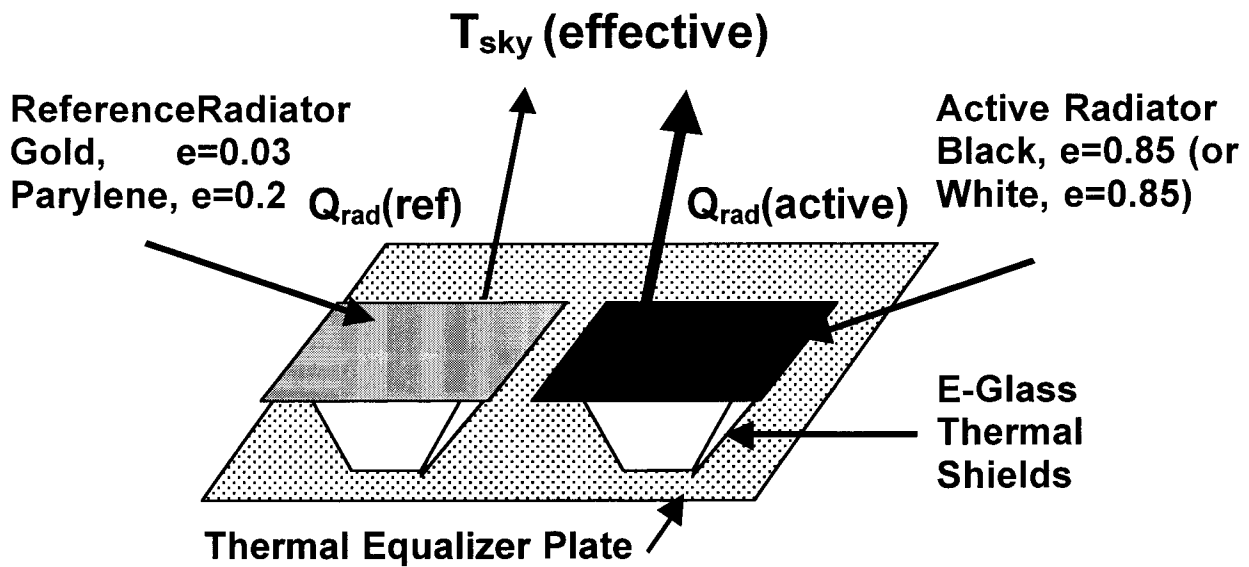


Figure 1. MTERC Experiment Design Concept (Low- ϵ vs. High- ϵ Comparison)

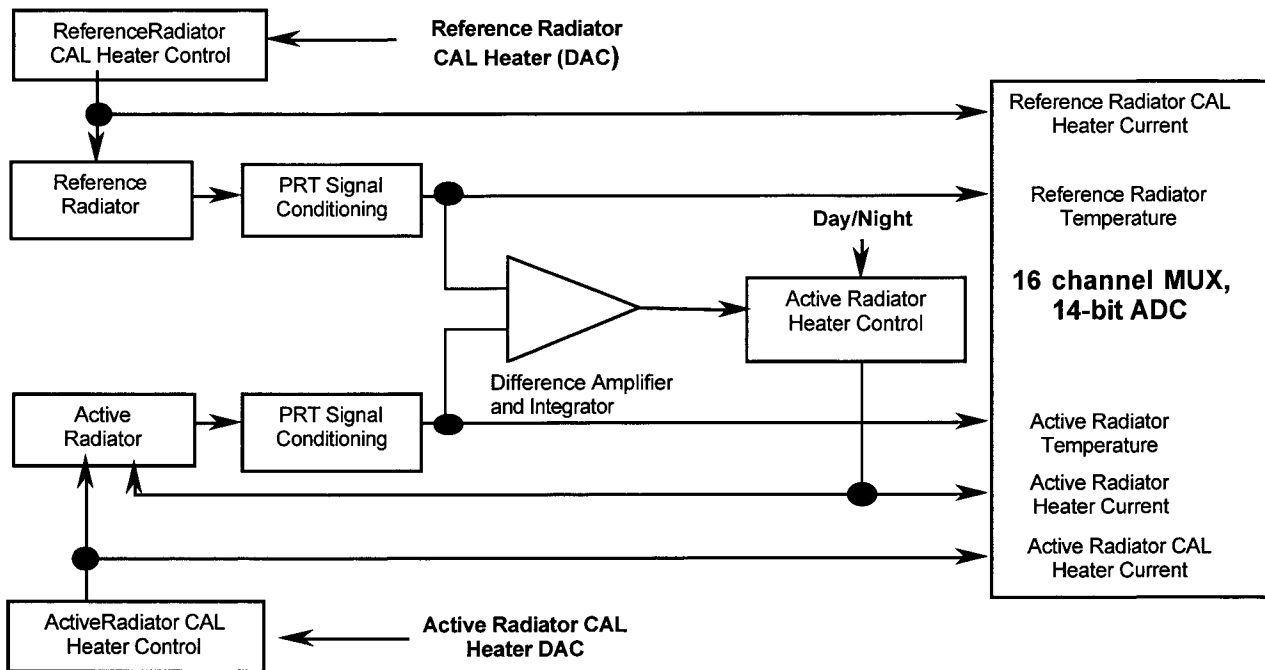


Figure 2. Functional Block Diagram of Differential Temperature Control Circuit

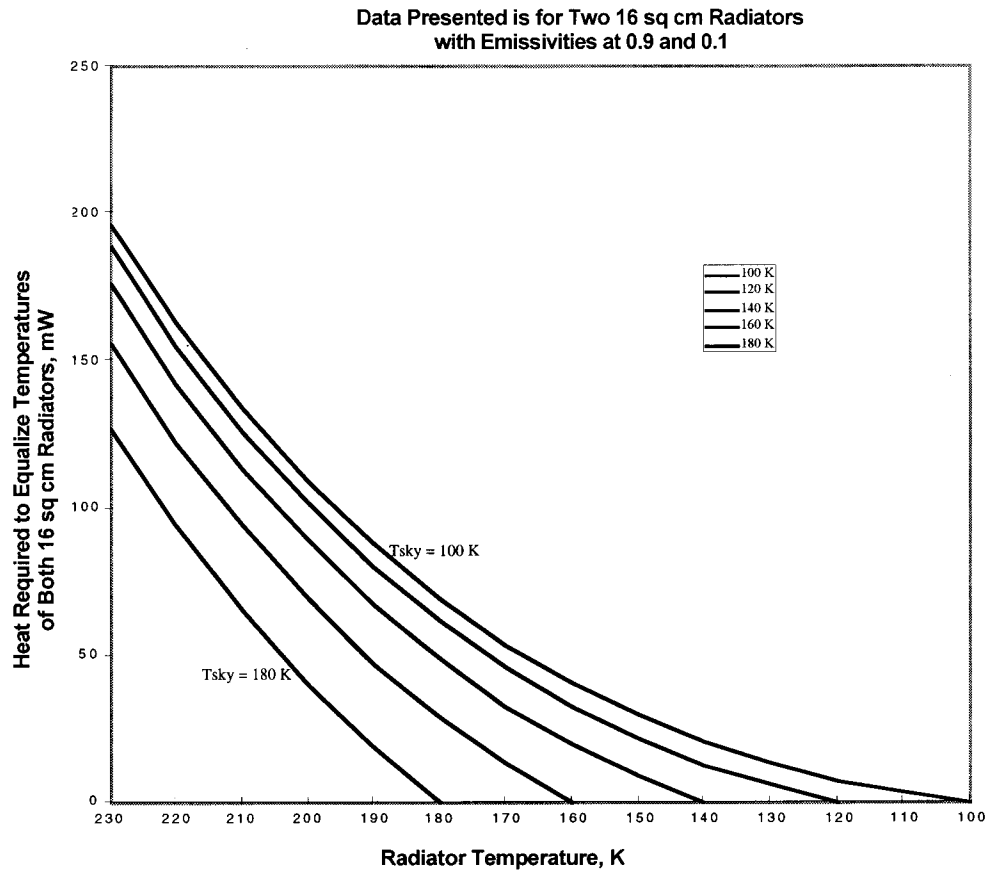


Figure 3. Plot of ΔQ_{htr} as a Function of Radiator Temperature at Different Sky Temperatures

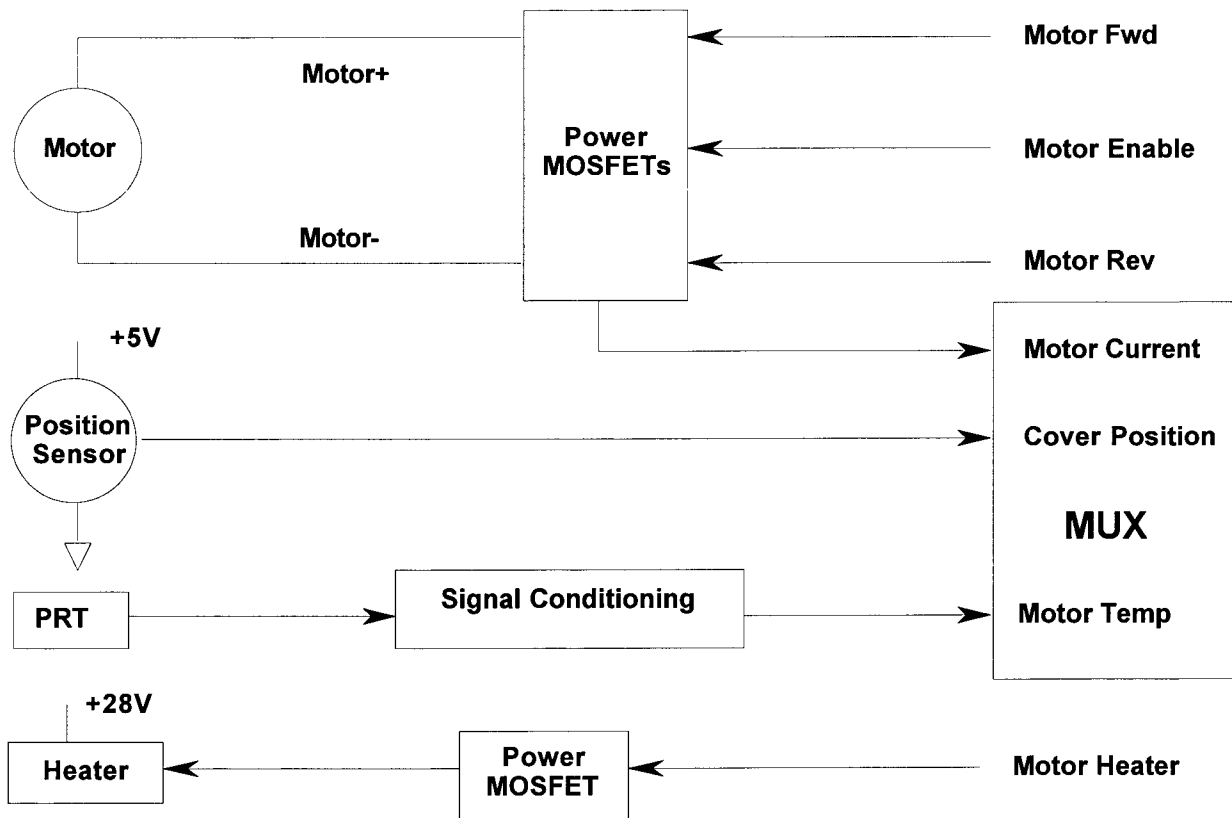


Figure 4. Functional Block Diagram of Motor Control Circuitry

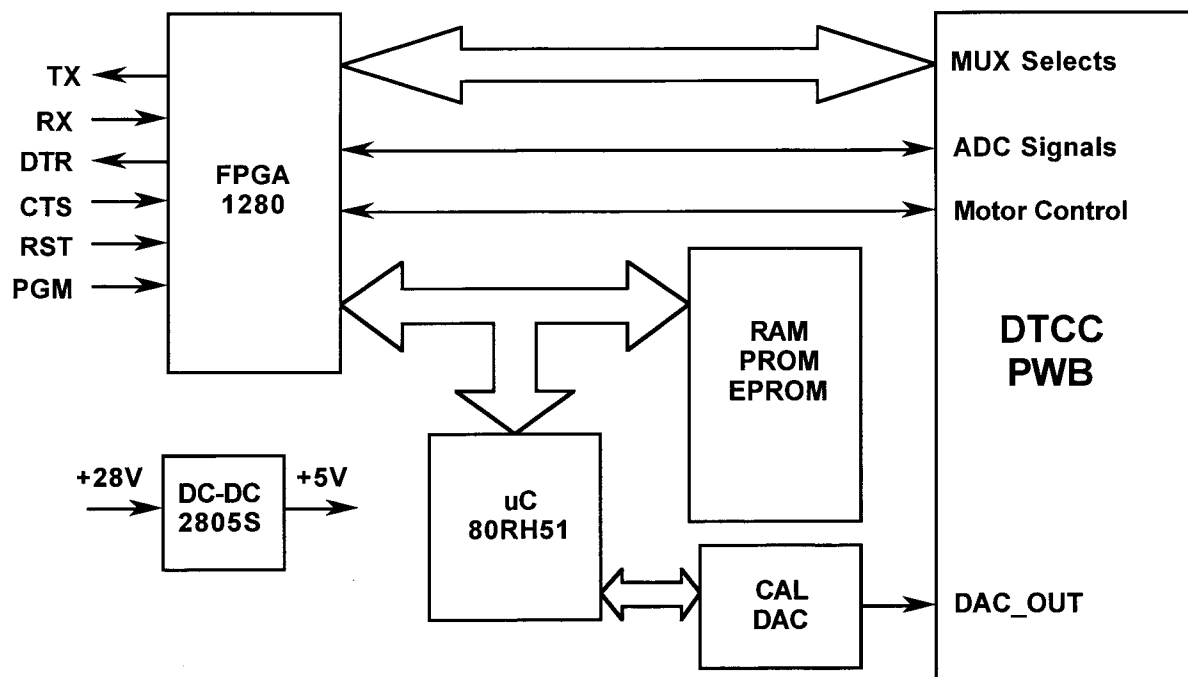


Figure 5. Functional Block Diagram of the CDH Circuitry

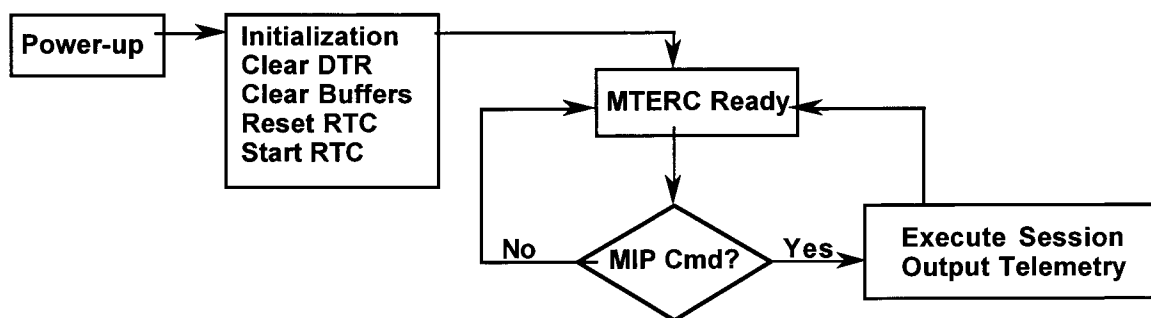


Figure 6. Basic MTERC/MIP Communications

- MTERC is tested in a thermal chamber configuration as shown to the right
- Sky plate is controlled to various temperatures from 120K to 180K by cryocooler fitted with trim heater
- Sky plate temperatures are calculated from input power and emissivity differences between radiator pairs $T_{sky} = [T_{rad}^4 - \Delta Q_{htr} / (\Delta \epsilon) A \sigma]^{1/4}$
- Calculated sky plate temperatures were consistently higher than actual sky plate temperatures
- Potential parasitic heat leaks:
Thermal radiation from MLI shroud to sky plate reflected onto MTERC radiators
Non-equivalent heat paths through radiator thermal shields (small effect!)

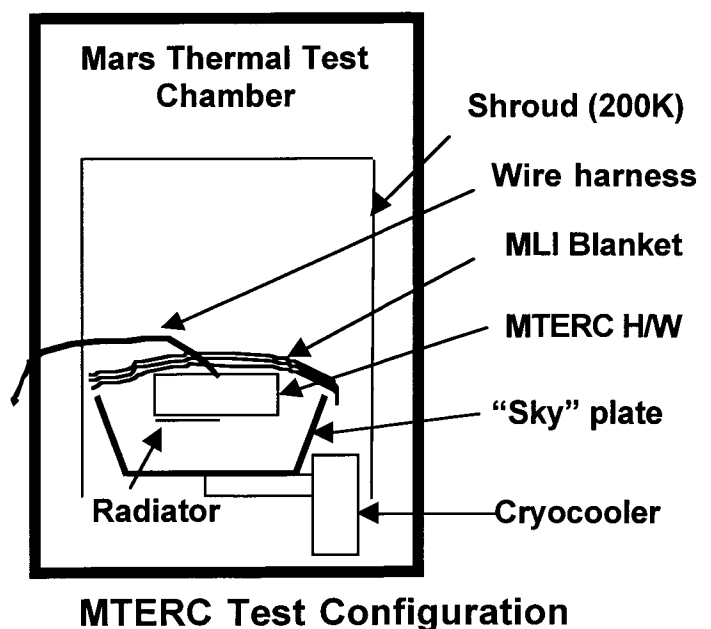


Figure 7. MTERC Test Setup

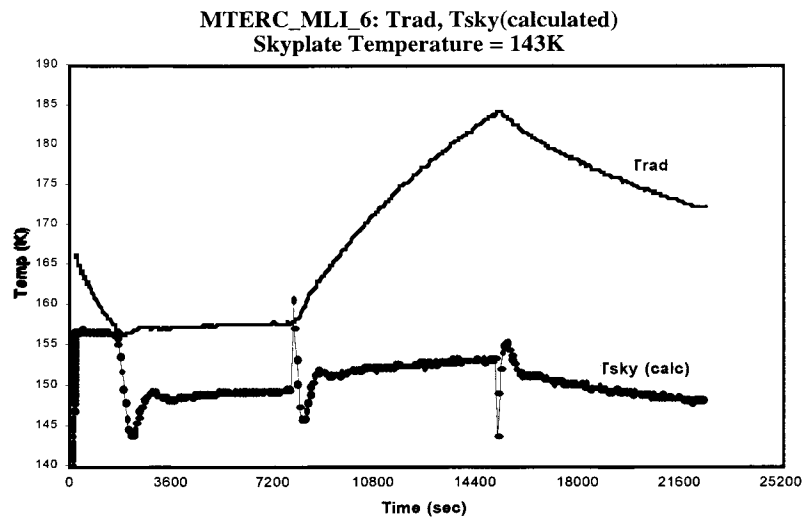


Figure 8. Calculated Sky Temperatures as a Function of Radiator Temperature

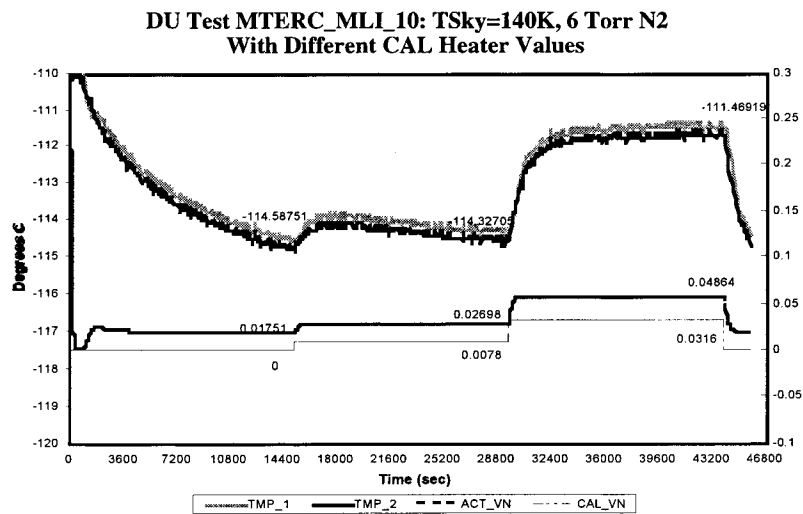


Figure 9. Active Radiator Tracking as a Function of Calibration Heater Power

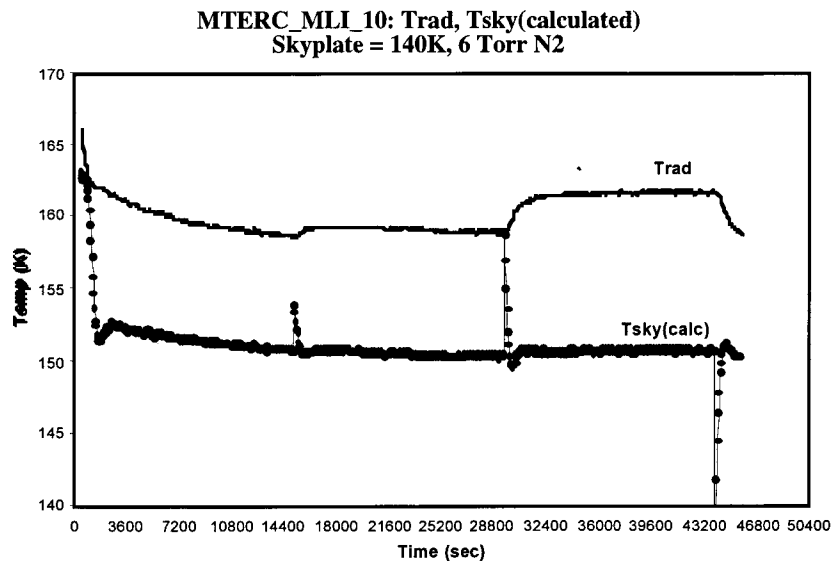


Figure 10. Skyplate Temperature Determination with Actual Skyplate at 140 K

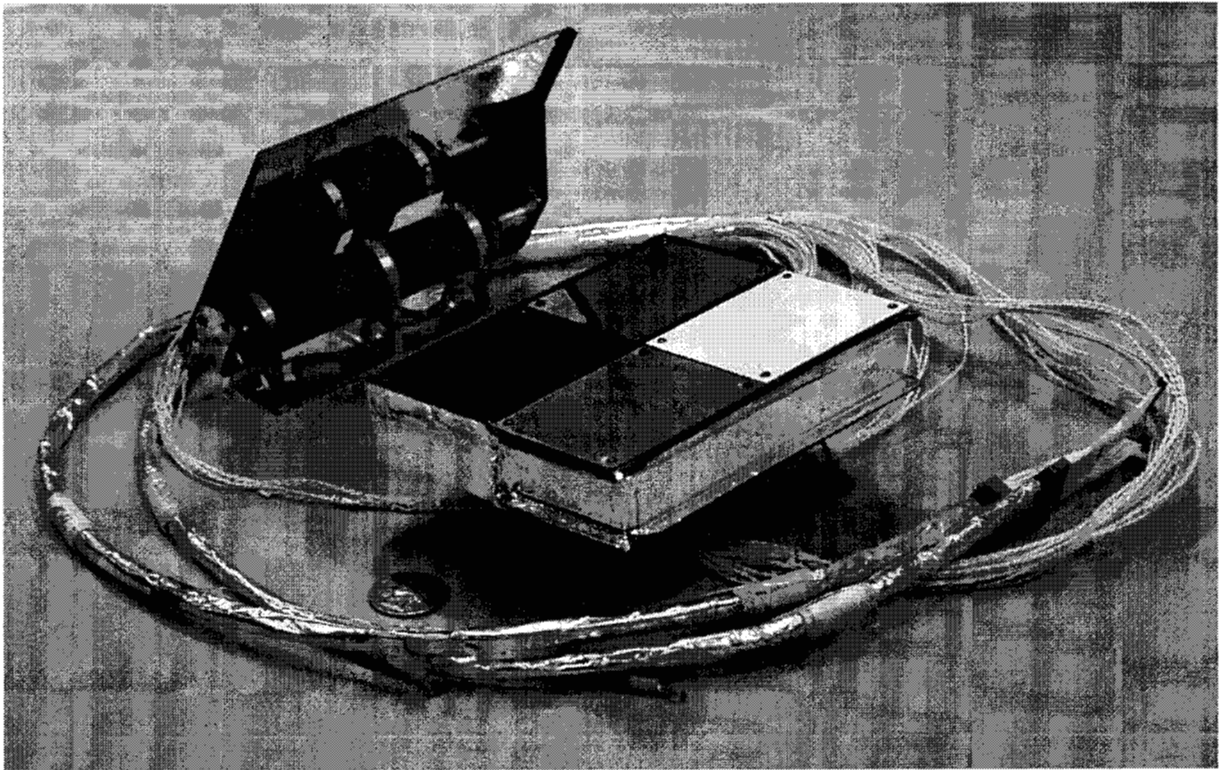


Figure 11. Photograph of the MTERC Qualification Hardware (12/6/99)